Design Rules and Issues with Respect to Rocket Based Combined Cycles

Tetsuo HIRAIWA

hiraiwa.tetsuo@jaxa.jp

ABSTRACT

JAXA Kakuda space center has been studying rocket based combined cycle engine for the future space transportation system. This note summarized design process and points that required for detail investigation. Moreover, this note presents our design example of the engine and experimental results with a sub-scale engine tests from the sea-level to the hypersonic conditions.

1.0 GENERAL ASPECTS OF THE ROCKET BASED COMBINED CYCLE

In this section, as a introduction to the rocket based combined cycle engine (RBCC), several key points of the RBCC will be picked up and discussed from the entire aspect and characteristics of the engine system.

1.1 Functions and Parameters for RBCC

Historically, RBCC engine is designed a system based on a rocket engine with air-breathing engines, such as ramjet engine. However, spreading our activities of the air and space, RBCC is now has functions and parameters widely. Typical functions are shown in Fig.1. Typically, RBCC is he ram/scramjet engine combined with the rocket engines in it.

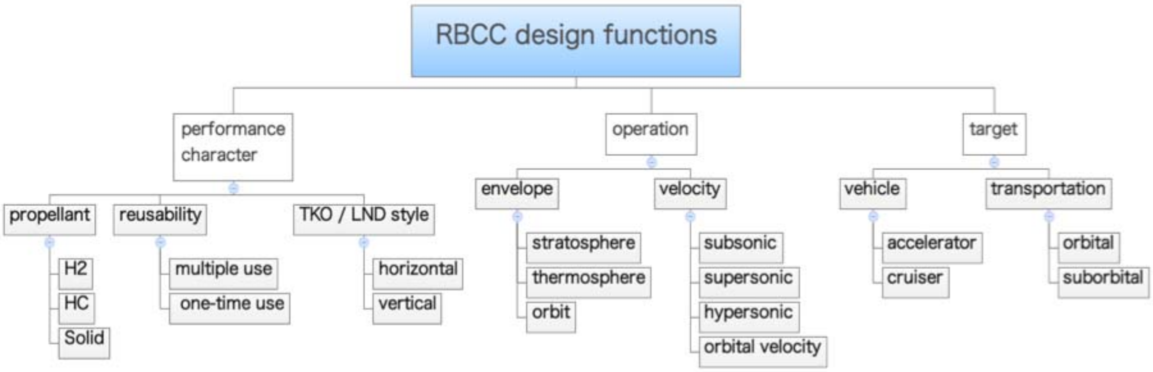

Figure 1: List of the RBCC design functions.

1.2 Key Point for the RBCC Design

Major objective of the vehicle that the RBCC engine will be installed must be indentified. What type of the vehicle required the RBCC engines? If the launch vehicle uses the RBCC as a primary system, the RBCC should be an engine for accelerating. Otherwise, it will be an engine for cruising in the atmosphere. This point change the balance in the performances between the rocket and air-breathers.

The effective Isp for the vehicle with the RBCC can be written as below:

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14. ABSTRACT
JAXA Kakuda space center has been studying rocket based combined cycle engine for the future space transportation system. This note summarized design process and points that required for detail investigation. Moreover, this note presents our design example of the engine and experimental results with a sub-scale engine tests from the sea-level to the hypersonic conditions.

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$$\Delta V = Isp \cdot \left(1 - \frac{D}{F_{eng}}\right) \ln \frac{m_0}{m_1}$$
$$= Isp_e \cdot \ln \frac{m_0}{m_1} \qquad (1)$$

Here, D is the drag of the vehicle, m_0 and m_1 are the mass of the vehicle at the initial and final conditions, respectively. For the accelerator, ΔV should be positive. However, for the crusier, ΔV can be unity at the certain flight condition.

Figure 2 shows the effective Isp profiles in the several Mach numbers, plotted with the mass flowrate from the rocket, m_r and from the air-breather, m_a [1]. In the faster flight condition, rocket engine in the RBCC should be worked as a major power source for accelerating the vehicle.

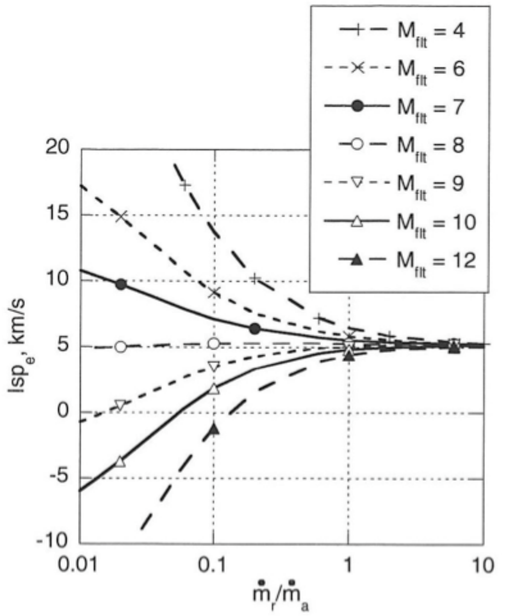

Figure 2: Effective Isp profiles with flight Mach number.

2.0 DESIGN POINTS AND PROCESS

RBCC design mainly process with iterating calculation for the internal engine configuration, i.e., inlet and combustor/rocket engine and their operating ranges. In the following section, as mentioned before, design issues of the integrated configuration, i.e., the rocket engines are embedded within the ram/scramjet flow pass, are described. Figure 3 shows an example of designing process for the RBCC engine.

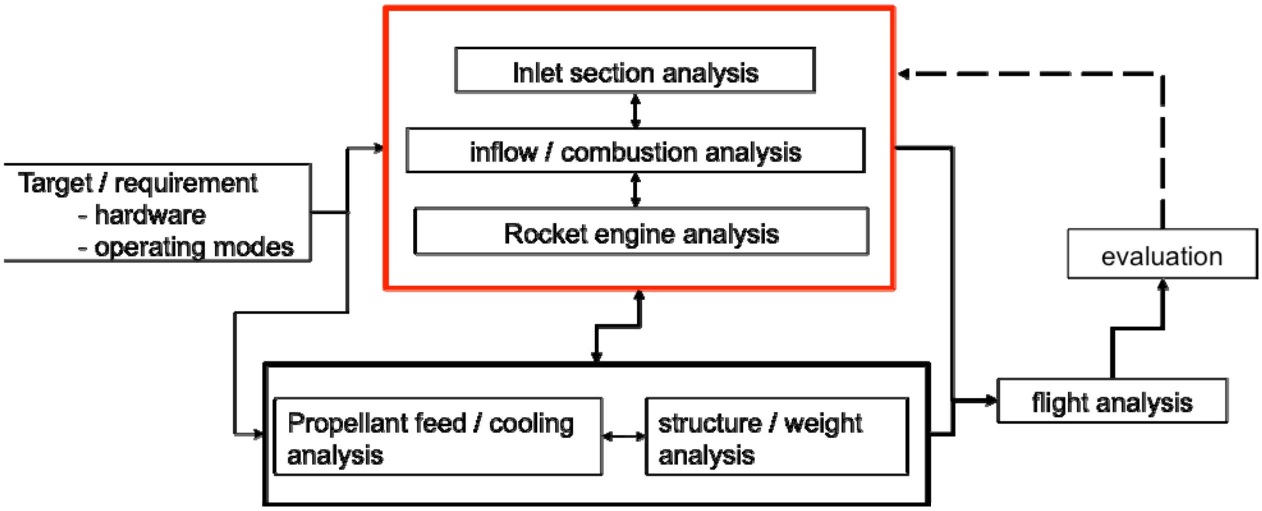

Figure 3: Design process for the RBCC system study.

2.1 Internal Engine Configuration

2.1.1 Inlet Section Analysis

As we seek for the accelerator, the inlet design is quite art of compromise. To make benefits due to air-breathing propulsion, the inlet should 1) start at as low speed as possible, 2) capture as much air-flow as possible, and 3) have as high compression as possible. The last requirement is also to give room for the rocket engine installation. Furthermore, 4) shortening the whole section, is important to reduce the engine weight. As one can see, these requirements conflict with each other, e.g., a large contraction and/or high capture design can worsen the starting characteristics, a longer inlet with less ramp angle will increase the engine weight, and so on. For trade-off, however, the operation range of the air-breathing propulsion part should be specified.

To reduce the length with sufficient performance, a multi-ramp design with a drooped cowl leading edge with limited sidewall compression ratio was selected. Figure 4 shows the design evolution of the drooped cowl [2, 3]. Length of the cowl as well as the droop angle was so adjusted that the cowl shock would not hit the ramp surface to cause separation at upstream of the throat. By this adjustment, starting capability of the inlet was enhanced with little sacrifice of the capture capability.

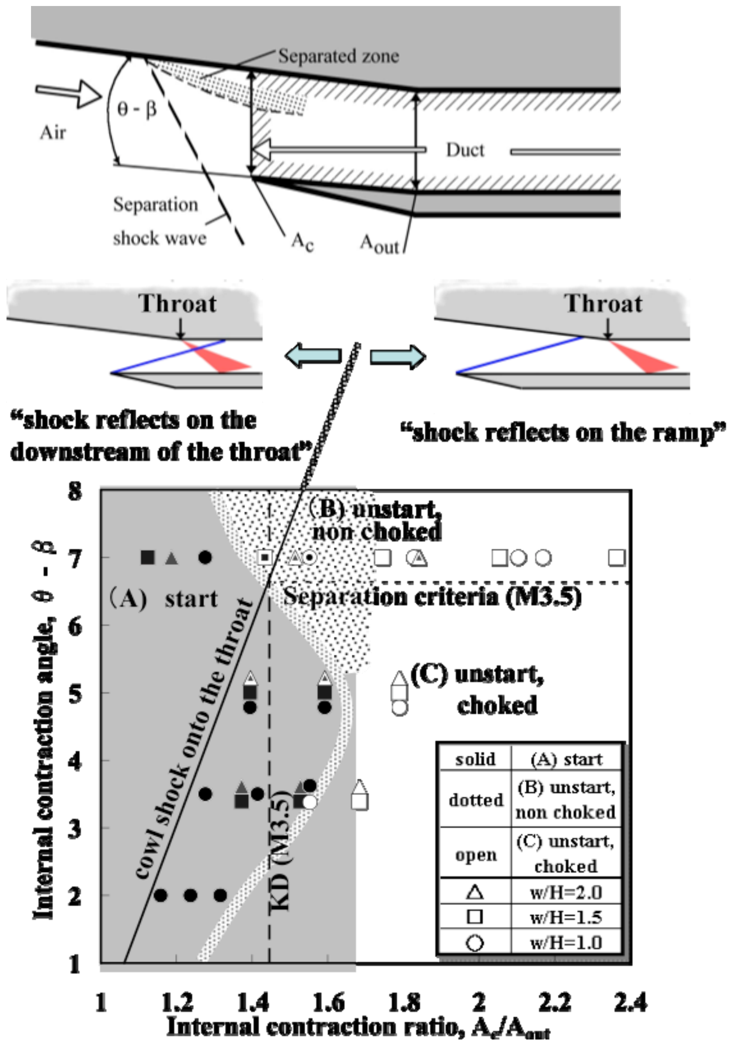

Figure 4: Inlet configuration study seek or wider starting range improvement.

2.1.2 Combustor Section Analysis

Embedded rocket chamber should produce sufficient thrust to takeoff and to overcome the drag at transonic regime. When embedded into a flow pass, the rocket exhaust can cause thrust augmentation due to the ejector effects, which in turn, can reduce the requirement for the rocket engine output. In the speed regime with the air-breathing propulsion, the rocket chamber should be operated at a reduced output to suppress the oxygen consumption. The rocket engine, on the other hand, can be used as ignition source for the ramjet-fuel. The rocket engine operation (output and mixture ratio) should be determined in a way that it can ignite the airflow/ramjet-fuel mixture.

Combustor design

The ramjet combustion chamber design is also an art of compromise, between the ejector-jet operation and ramjet operation, between the ramjet operations at various flight conditions, and between the ramjet operation and pure rocket operation for SSTO system. The balance between the performance and the engine weight also has a sizable impact of the system performance.

To attain ejector-effects, a rather long mixing duct with constant area duct is required. Figure 5 shows prediction of the air-suction performance with a physical model shows atop, in the case with the cold rocket (primary flow) injection [4]. To attain pressure balance between the airflow and rocket, a certain length was required.

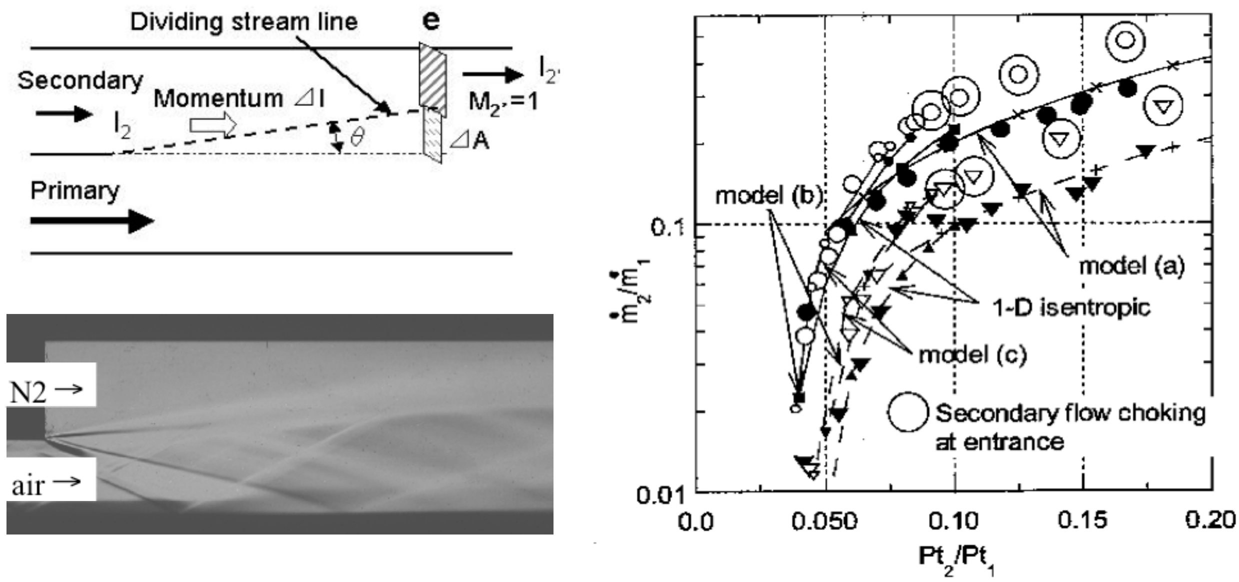

Figure 5: Ejector modelling (upper left), cold flow example (lower left) and ejector prediction profiles.

The ramjet-combustor also should have a certain length, to contain the pseudo-shock wave system within it to avoid transition to unstart condition, and to attain sufficient mixing and to sustain combustion. However, as the engine weight was estimated as deadly heavier in our analysis, shortening the combustor has priority in our analysis.

As for the containment of the pseudo shock wave system, the propagation length within diverging duct should be predicted based on momentum balance. For the prediction, pressure distribution within the pseudo shock wave system should be identified. Starting with linier model, we came up with a better prediction by introducing square-root model as shown in Fig. 6.

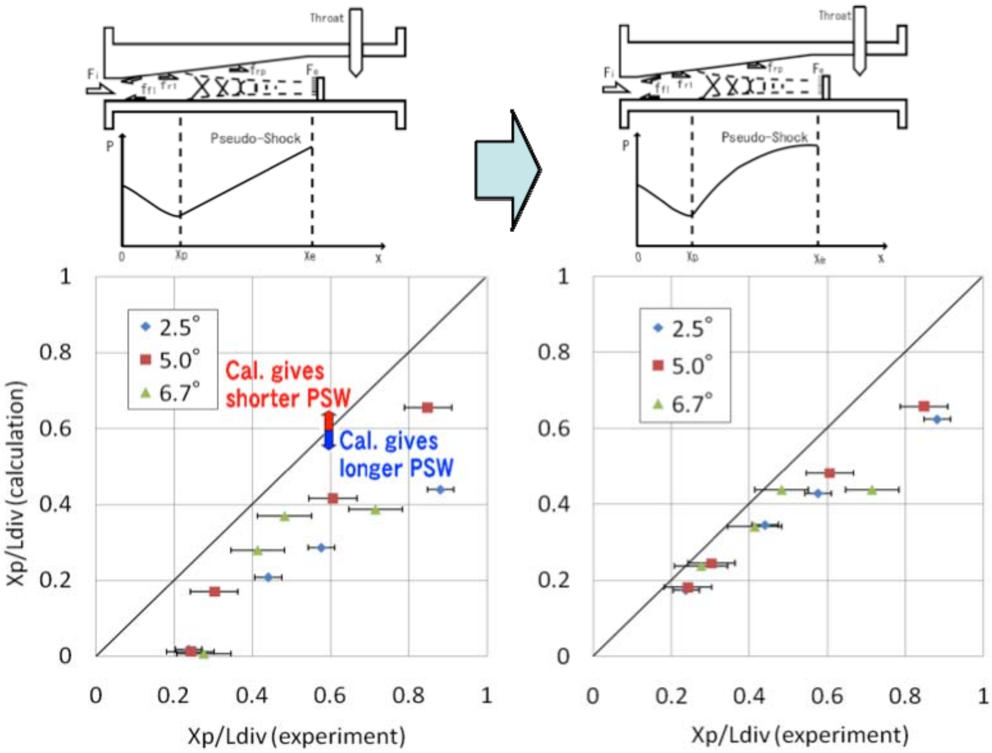

Figure 6: Pseudo-shock system study example for the combustor design.

For the ramjet-combustion, also a certain length is required to sustain mixing and reaction, however, the length should be reduced in system point of view. To shorten the ramjet-combustor, diverging angle should be large. However, a larger diverging angle around the fuel injector resulted in a lower pressure rise in ramjet operation, so that the diverging section should be nicely contoured to have smaller diverging angle around the ramjet-fuel injector. An example was to place a constant area duct to sustain combustion, and was found to attain good combustion capability, as shown in Figure 7 [5]. However, this portion would add additional weight, cooling requirement, and friction loss.

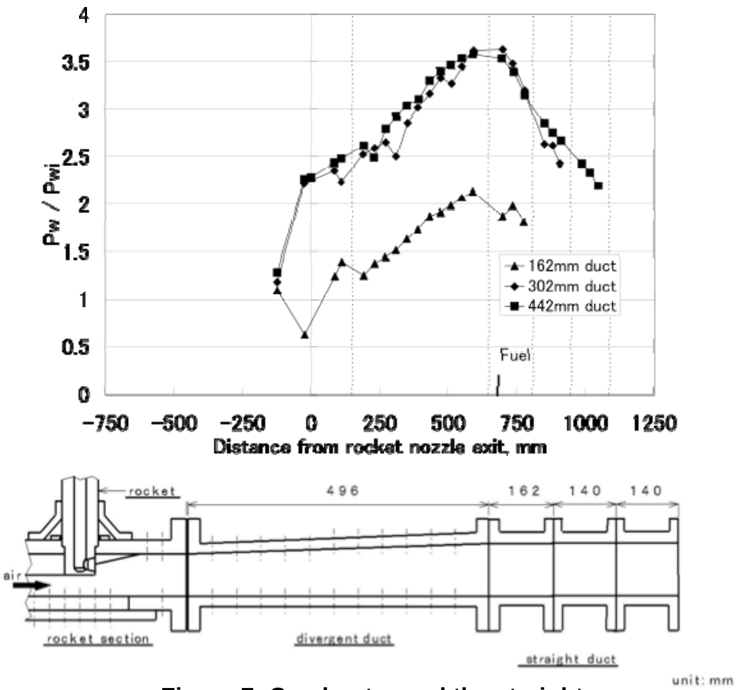

Figure 7: Combustor and the straight duct design experiment.

2.2 Operating Conditions of the RBCC System

The ramjet operation is the key to increase the specific impulse, so that a wider ramjet operation is essential to the RBCC system for accelerator. To enlarge the ramjet-operation range to a lower Mach number regime, so called dual-mode combustion should be applied to Mach number as low as M3. Below that, as shown in previous figure, ramjet performance drops rapidly. The RBCC system should have margin between the inlet-start Mach number and lower limit of the ramjet operation, as unstart transition of the engine is fatal to the flight of the vehicle. At low Mach number regime, dual-mode operation with thermal choking at the end of the diverging section is beneficial as more fuel can be introduced for more thrust production. Controlling the choking location with the flight Mach number can result in additional gain in Isp, which should be in trade-off with the system and control complexity.

At higher Mach number regime, thrust production of the air-breathing engine part decreases with the increase in the airflow enthalpy. With the decrease in the thrust level, the ramjet operation becomes inefficient for the acceleration because airframe drag to thrust ratio is reduced. As results, the effective Isp, i.e., Isp*(1-drag/thrust), eq (1) increases with the rocket engine output at higher Mach number regime (M>7 in our analysis). With an addition of large momentum by the rocket plume, dual-mode operation is no longer available, so that the ramjet combustor will operated as scramjet. The upper limit of the air-breathing engine operation depends on the system performance, M11~12 in our analysis.

Figure 8 is an example for the RBCC geometric and operational design for the accelerator, based on the design process above.

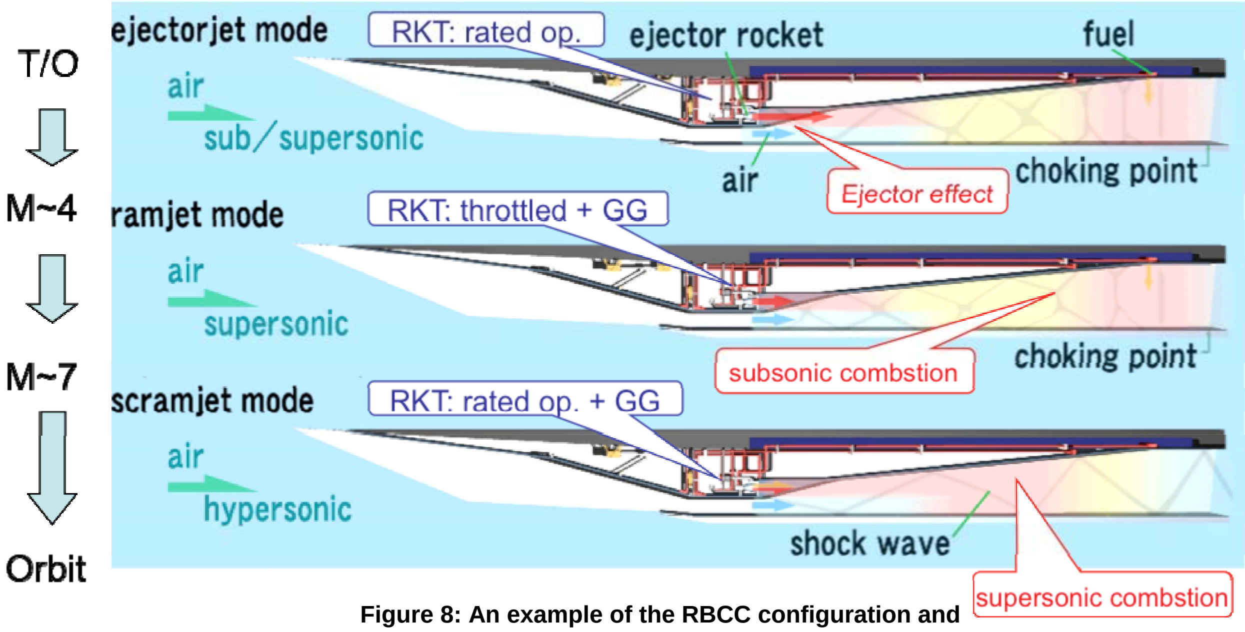

Figure 8: An example of the RBCC configuration and operational range based on the design process.

3.0 SUB-SCALE TEST FOR DESIGN WORK

As a part of our design process, a sub-scale engine was constructed and tested to obtain the characteristics of the RBCC engine entirely, that could contribute to the engine design results discussed in the previous sections.

3.1 Sub-Scale Engine and Testing Facility

A sub-scale engine, designated as E3, has 2D internal flowpath and 2 rocket engines installed in the middle part of the body [6]. The rocket engines powered with gas-hydrogen and oxygen is in the middle and topwall side of it. In the combustor section, there are fuel-injection ports on the top and sidewalls. These injectors inject gas-hydrogen vertically toward the airflow / rocket plume.

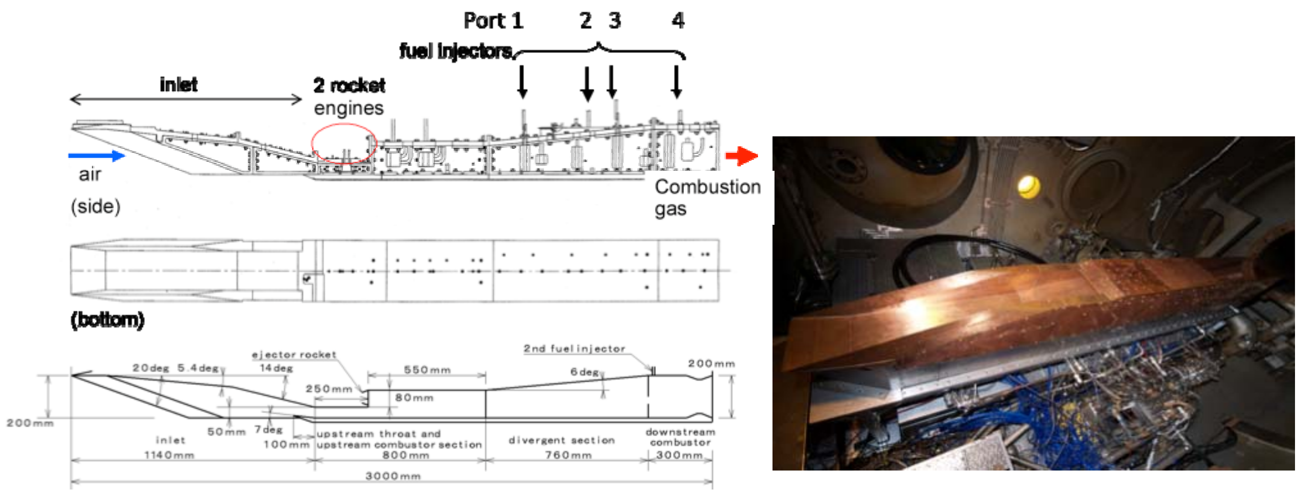

Figure 9: 3 m-length, sub-scale RBCC engine for the design validation process.

This engine was tested in our engine test facility, named Ram-Jet engine Test Facility, RJTF. The RJTF was designed to operate at Mach 4, 6, and 8 for flight altitude of 20 km, 25 km, and 35 km, respectively.

3.2 Engine Test Results and Evaluation

Ejector-Jet Mode Test

Figure 10 shows wall pressure distributions on both top wall and cowl at the exit contraction ratio of 1.11 without secondary injection or about 30 g/s of injection through port #2 [7]. Results with the drooped cowl leading edge geometry were shown.

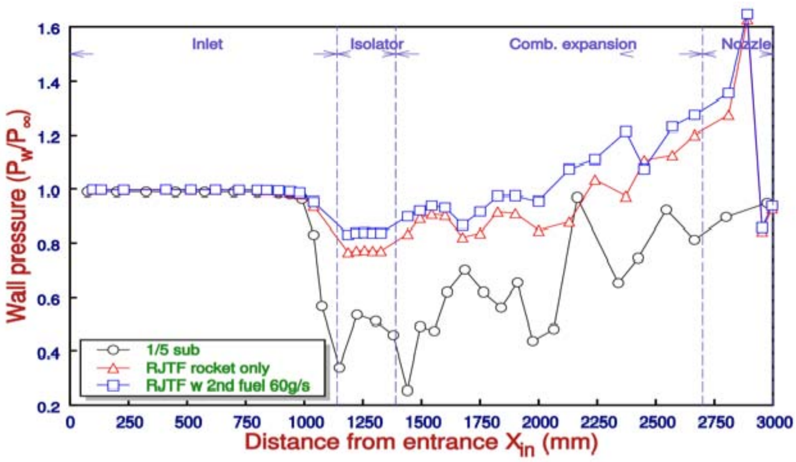

Figure 10: Ejector-mode operation results of E3 engine.

Pressure-level in the vicinity of the rocket nozzle exit (around 1350mm, the end of isolator section) was about 0.9 × back-pressure, far above the design value for choking (0.5 × atmospheric pressure). Consequently, the airflow rate was reduced to about 1.5 kg/s, from the design value of 2.1 kg/s in the choked case (30 g/s of secondary fuel corresponded to 0.5 in equivalence ratio against the design airflow rate).

This lower ejector performance has been analyzed with computationally and experimentally. Figure 11 shows the CFD result simulated not only cold–gas but the plume from the rocket engines. The ejector performance becomes lower because of the mixing between the incoming air and the rocket plume and the back-pressure rising caused by the heat release in the mixed flow. This result was also confirmed by the sub-sonic, flight experiment of the ejector on the sounding rocket [8].

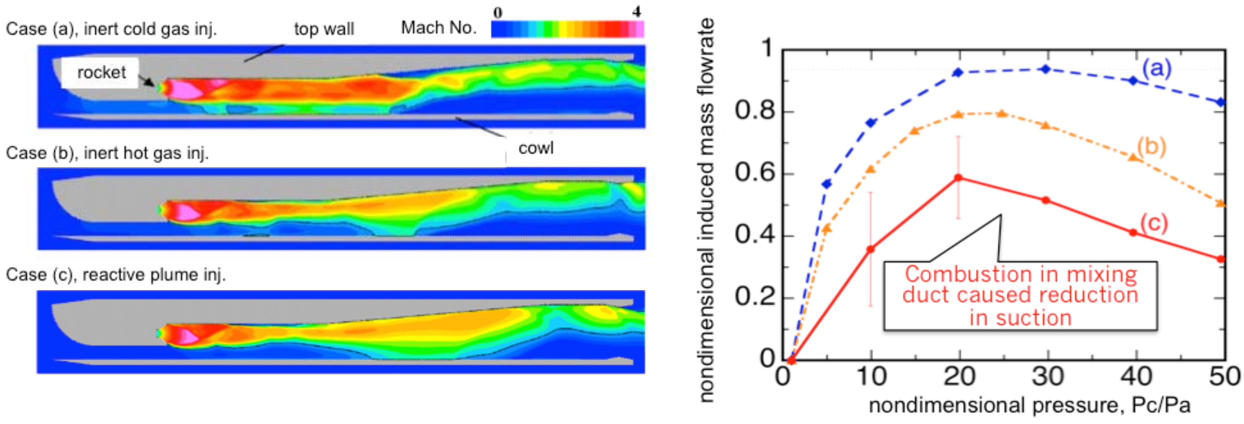

Figure 11: CFD simulations for the ejector effect with various gases included the rocket plume (case C).

M6 Ramjet mode test:

The major concern in the test at the M6 condition was achievement of ignition by the rocket plume as the ignition source, as lack of ignition capability in early scramjet model tests was quite a trouble [9].

Figure 12 shows wall pressure distributions (on top wall) at the ramjet-mode operation (Pc=0.65 MPa, O/F~6) with different secondary fuel injection locations (port #3 and #4) at M6 condition.

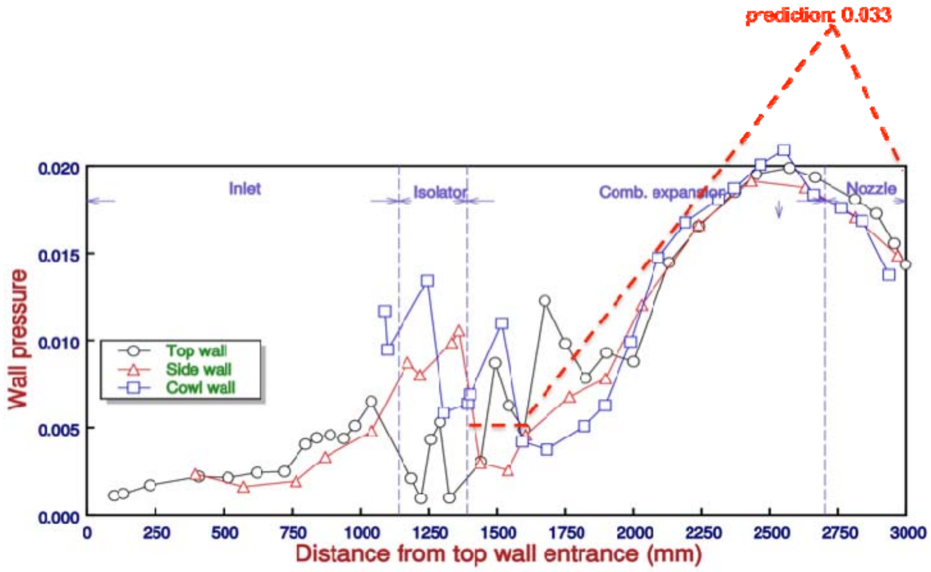

Figure 12: Ramjet mode pressure distributions with prediction based on the design process and tools.

Pressure profiles in the combustor section show their peak pressure around 0.020, about 30% lower than the predictions. The gross thrust obtained in the combustor (i.e., wall on the divergent area) is 730 N by this experiment and 830 N by the prediction.

4.0 SUMMARY

This note presented the designing process and key or critical issues for the RBCC development, based on the research work in JAXA Kakuda space center. Additionally, sub-scale engine results and their predictions also shown as example for the design accomplishment to date.

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